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# Finding and Studying Luminous Dust-Enshrouded Galaxies

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**Abstract.** This meeting was convened to celebrate the career and science interests of Tom Phillips. The possibility of investigating the physics and chemistry of the molecular interstellar medium (ISM) in galaxies, at mm/submm wavelengths has been enabled by many, but Tom's long-standing and consistent contributions are amongst the greatest. Here I will summarize some of the key developments and prospects for better understanding galaxy evolution, by exploiting the energy generated by stars and active galactic nuclei (AGNs) after it has been absorbed and reprocessed by the solid and gaseous components of the ISM. I highlight the difficulties of identifying and diagnosing the discovered objects. The initial burst of activity associated with the galaxies detected when the first mm/submm-wave imaging instruments were fielded is maturing; however, the advent of in particular *Herschel Space Observatory (Herschel)*, the Atacama Large (Sub-)Millimeter Array (ALMA) and the Cornell-Caltech Atacama Telescope (CCAT) mean that the complimentary view provided by far-infrared (IR) sensors to reveal both the detailed astrophysics of star formation taking place star by star, and of the great bursts of activity seen across the Universe is becoming much more powerful.

## 1 Introduction

The development of instrumentation to detect submm photons has reached the point of maturity where both the largest ground-based astronomical facility ever built (ALMA), and the recent flight of the flagship space missions, *Herschel* and *Planck Surveyor* are all enabled by this instrumentation, and dedicated at least in part to the science of the interstellar medium, near and far. The detectors to measure this radiation, along with the supporting technical infrastructure for cooling, linking and multiplexing the signals has been developed steadily, with suitable quantum-noise/background-limited detector performance being demonstrated first using ground-based mm/submm-wave antennas at high-mountain sites. The availability of such telescopes also motivated the development of imaging bolometer systems, including the first wide-field camera Submillimetre Common-User Bolometer Array (SCUBA). The *Kuiper Airborne Observatory (KAO)* also provided a long-term line of support to develop cutting-edge instrumentation at wavelengths where the atmospheric conditions were more challenging. The technology has been steadily advancing required to justify often worldwide projects of the scale of *Herschel*, ALMA, and the *Stratospheric Observatory for IR Astronomy (SOFIA)*. All of these facilities have enabled technology for the next-generation of far-IR and submm-wave cameras, including the suite of instruments SHARC, SHARC-2, BOLOCAM, and MKIDCam at the Caltech Submillimeter Observatory (CSO) that Tom's efforts have made available.

## 2 A New View of the Universe

The fruits of these technical developments have been a new way to image useful areas of sky populated by faint and distant galaxies at previously unexplored mm/submm wavelengths. Both developments for space-borne systems, and available observing resources on the ground have allowed this progress, feeding back to support further generations of suitable missions, along with a genuine broadening of our understanding of the formation of galaxies.

Before sensitive SIS junction devices were in prospect, it was unreasonable to build large ground-based facilities for mm/submm-wave observations, or to fly dedicated space missions to probe these wavelengths. The IRAM telescopes, the now-decommissioned SEST, the CSO, Nobeyama telescopes, JCMT, and other smaller facilities, including KOSMA in the Swiss Alps and ASTRO at the South Pole, provided testbed facilities for receivers, and tantalizing scientific results that testified to the power of probing the molecular Universe, and the richness of information that was available by using the three decades of wavelength between the atmospheric cutoff for radio waves at about 40 GHz and the opening of near-IR windows at around $5\,\mu$m.

These single-dish telescopes were traditional radio antenna designs, with a small field-of-view. Motivated by studies of objects in molecular clouds at kpc distances, observations using single-pixel bolometers (e.g., Isaak et al. 1994) confirmed that the most luminous objects at Gpc distances could be detected at submm wavelengths, and confirmed with thermal dust spectra. However, the technology to field cameras with arrays of bolometers on these telescopes were developed, both to allow much faster mapping of galactic targets, and to survey enough sky to allow new classes of very luminous galaxies to be discovered at these telescopes, extending our knowledge of the dusty, molecular Universe out to high redshifts.

The arcmin-scale fields of view provided by these telescopes, were filled with hand-crafted bolometer arrays, and their use lead to sub-square-degree scale deep surveys using this suite of instruments, including SCUBA, MAMBO, SIMBA, and the CSO's SHARC. The next-generation of cameras incorporated more monolithic detector arrays, including SHARC-2, BOLOCAM, LABOCA, and AzTEC.[1] All these surveys, made from different sites, telescopes, conditions and wavelength bandpasses have demonstrated a reasonably coherent picture of the brightness distribution of very powerful dusty galaxies on the sky, with total luminosities in the range from about $5 \times 10^{12}$ to several $10^{14}\,\mathrm{L}_\odot$. Wider-field, higher pixel count cameras are now being developed, including SCUBA-2 and MKIDCam.

[1] The core of AzTEC is a JPL-developed spider-web bolometer detector wafer.

### 2.1 Distant Galaxies Using Tools Built to Study Local Star Formation

The feature of the spectral energy distribution of thermal emission from dust that enables these surveys is the redshifting of the steep Rayleigh-Jeans tail of the composite emission from the different clouds of dust at different temperatures and from different regions within a distant galaxy allows a larger fraction of the total energy emitted by the galaxy to make its way into the mm/submm-wave observing window (see Blain et al. 2002 for a summary and a discussion of some selection effects, see also Chapman et al. 2008). The restframe thermal spectrum of the clouds of dust in the the interstellar medium of a powerful galaxy peaks at anywhere between 20 $\mu$m in some powerful AGN, to 200 $\mu$m in a galaxy like the Milky Way. Nevertheless, even the most local, coolest object has a steeply rising spectrum longwards of the 350,$\mu$m atmospheric window. This biases surveys for luminous dusty galaxies to select cooler galaxies for a given total far-IR luminosity, and means that the flux density received from a galaxy with a fixed restframe spectral energy distribution and total luminosity is almost independent of redshift from $z \simeq 0.5$ to 10.

The processes that cool molecular clouds to enable star formation in the local Universe appear to be at work in the most distant objects too. Molecular spectral diagnostics and atomic fine-structure transition emission currently follow behind the detection of the much more luminous continuum emission for detecting distant galaxies. However, these tools are available to better understand the conditions in the interstellar medium of the most luminous galaxies, out to reionization and beyond.

### 2.2 The Power and Frustration of Observing Faint Targets Through the Short-Wavelength Atmospheric Windows

Dating back to the late 1990's Tom Phillip's desire to equip CSO with the best receivers lead to the first short-wave submillimeter-wave camera, SHARC (named to counter the JCMT's SCUBA, fielded in 1997), a $2 \times 12$ array of pixels optimized for 350 $\mu$m. In an ESA meeting in Spring 2007, Tom Phillips presented a 350 $\mu$m image in the direction of the Hubble Deep Field-North, the first useful limit to the surface brightness of distant dusty galaxies. The full availability of the JCMT's SCUBA camera later in 1997 allowed the first detections to be made.

SHARC-2, a $12 \times 32$ array of Goddard-sourced detectors, providing the first fully-sampled submillimeter-wave focal plane instrument, and an imaging field well matched to the CSO field of view has for half a decade provided a unique high-quality, fine-spatial resolution imaging array at 350 $\mu$m (Beelen et al. 2006; Coppin et al. 2008; Kovacs et al. 2006a). The safe route would be to take advantage of more typical useable weather in the 350 GHz and 230 GHz windows, but CSO has been able to exploit an advantage for imaging performance in excellent weather, via both SHARC and SHARC-2, and via high-frequency SIS receivers, while maintaining a suite of capable receivers for less excellent weather, including the fast-mapping capability of the BOLOCAM 1100 $\mu$m camera. The careful attention to calibration, atmospheric correction and imaging quality from analysis of SHARC-2 and BOLOCAM data has also provided important techniques for use on other facilities, with Sayers et al. (2009) and Kovacs (2006b) having provided new insight into the way to best extract true structure from modest-scale, cross-linking maps.

An active dish surface system (DSOS; Leong et al. 2006) has substantially improved the aperture efficiency of the CSO to take better advantage of the best conditions. Once they have cooled at night, ALMA's 12 m carbon-fiber antennas have an excellent, uniform surface accuracy, but costs ensure that future larger apertures cannot easily take advantage of the stiffness of composite structures, and so active control of precision surfaces on more flexible steel support structures is a necessary step in order to achieve the scientific goals of CCAT[2] for example. The heritage of elegant solutions to structural problems typified by the engineering of the Leighton antennas used by CSO and the six 10 m antennas of CARMA has continued, keeping the CSO as the most efficient submillimeter-wave telescope prior to the era of ALMA. The development of ALMA antennas allowed the technology to be exploited to deploy similar telescopes at the South Pole (the US-lead South Pole Telescope—SPT) and Atacama (the European-lead Atacama Pathfinder Experiment—APEX, Japanese Atacama Submillimeter Telescope Experiment ASTE and US-lead Atacama Cosmology Telescope—ACT). Note that even with these more advanced telescope designs in service, the CSO retains a significant advantage in deployed imaging capabilities at the highest-frequency windows, already operating at the shortest wavelengths.

The ability to measure an accurate 350 $\mu$m flux density for galaxies detected at the longer wavelengths provides a way to constrain accurately their total luminosity. Taken as a proxy for the total IR luminosity, the synchrotron/free-free radio continuum flux density of a galaxy can also provide this kind of constraint; however, this requires the assumption of the continuation of the tight far-IR–radio correlation (in this context see references in Carilli & Yun 1999) that is well-established at low redshifts from the *IRAS* mission out into the distant Universe. SHARC-2 data for distant ultraluminous objects suggests that the radio flux is in fact subtly enhanced with respect to this standard, and so the total power derived from a radio flux, assuming the local far-IR–radio relation is actually greater by a factor of about two as compared with the value derived from a direct measurement of the far-IR thermal spectrum. This has interesting consequences for the astrophysics of the interstellar medium in these galaxies, indicating possibly higher magnetic fields, or a higher density, generating greater energy transfer to cosmic-ray electrons in supernova remnants, and of course provides an important qualification to the estimated contribution of the far-IR-loud population top the total energy production rate in galaxies (Blain et al. 1999a,b; Chapman et al. 2005).

## 2.3 Complementary Studies from Space, and Future Detectors

*Spitzer Space Telescope* imaging of the sky from the stable transparent position of an earth-trailing solar orbit has provided a wealth of data on the IR Universe. Nevertheless, the response of *Spitzer* at wavelengths shorter than 30 $\mu$m is very significantly better than at longer wavelengths, and so the peak of the spectral energy distributions of galaxies remain sparsely sampled.

[2] www.submm.org

In the next decade, larger format instruments, in some cases behind re-imaging optics will allow much more ambitious surveys. In particular, the 25 m-aperture CCAT performing surveys all the way to the atmospheric cutoff near 1 THz, will provide surveys of the obscured Universe with the depth and size to complement directly the legacy of *Spitzer* and the best deep optical/near-IR panoramic surveys that will be available until a space-based wide-field *JDEM*-type imager and a LSST-type ground based all-sky repetitive survey are available. The tools necessary to carry out these efforts are being developed, and tested on the sky, as described throughout this volume, and especially in the presentations by Glenn, Golwala, and Zmuidzinas.

## 3 Finding the Blobs and Understanding the Blobs that are Found

Owing to the modest signal-to-noise ratios of galaxies detected using mm/submm-wave cameras, their typical 10–20″ beams from 10-to-30 m aperture single-dish telescopes, the visual impression of the images is that of a beam-shaped, noisy "blob." While existing submm-wave surveys for galaxies provide a unique opportunity to identify a rich mixed bag of very luminous galaxies that are both typically at high redshifts and relatively difficult to identify as extreme objects at other wavelengths, they are not producing images that have any possibility of reproduction as art. The resolution of these images is never sufficient to reveal the internal structure of the detected objects, and in a significant number of cases nor is it sufficient to rule out the detected source actually being a blend of the emission from individual sub-units. This leads to a situation that is unprecedented since the advent of radio telescopes in the 1950's: that the noise in deep maps is dominated by the "confusion" noise floor imposed by the unresolved sea of undetected fainter galaxies that underlie a bright source. The effect of this confusion noise both limits the effective depth of an image, and owing to the pronounced high-flux tail of the pixel brightness distribution, that is much more extended than a Gaussian, it can lead to substantial excursions of the measured flux above the true flux of the source, leading to so-called "flux boosting" of sources listed in a catalog (Eales et al. 1999). This effect of confusion is best explored in simulations that are matched to a particular telescope, instrument and brightness threshold in the distribution of galaxies in the field; however, it can have a significant effect on the completeness and reliability of a survey (see Pascale et al. 2009). It will be of great interest for the analysis of images from *Herschel*-SPIRE and *Planck* surveys, which combine great sensitivity, with modest angular resolution.

### 3.1 Catalogs Compiled from Deep mm/submm Surveys

Based on a series of different surveys, several hundred targets have been found, using very deep (Smail et al. 1997; Hughes et al. 2008; Cowie, Barger, & Kneib 2002), and wider-field surveys (Barnard et al. 2004; Bertoldi et al. 2007; Coppin et al. 2006; Greve et al. 2008), and now even wider surveys (Pascale et al. 2009; Vieira et al. 2009), which probe a very representative volume of the distant Universe, and yet are shallow enough to take advantage of the *IRAS* and radio all-sky surveys to excise low-redshift candidate galaxies from the survey catalogs.

### 3.2 Identifying a Sample of the Same Galaxies at Other Wavelengths

Careful photometric work with multiwavelength catalogs (Dey et al. 2008; Capak et al. 2008 ) can yield optical–mid-IR-selected candidates, by the careful excision of galaxies with other properties using color-color criteria. In general, red mid-IR galaxies with faint optical counterparts can tend to yield submm-selected objects. The presence of detectable radio continuum emission is a good indicator of high total luminosity, although note that the detectability of radio emission for even the most luminous galaxies in the deepest radio surveys decreases rapidly with increasing redshift, and beyond $z \simeq 3$ in existing surveys, this is no longer a useful diagnostic.

An almost unaccountable wealth of such potential targets, selected primarily from colors found in the four bands of the *WISE* all-sky survey at 3.3, 4.7, 12, and 23 $\mu$m will hopefully start in early 2010;[3] however, the confirmation of all but a tiny fraction will be impossible using current facilities.

### 3.3 Understanding the Astrophysics of the Detected SMGs

In order to recognize the sources detected in submm-wave surveys, to find their distances and natures, via multiwavelength observations, deep supporting images and dedicated spectroscopy are necessary. It is reasonably easy to detect molecular gas rotational line emission from any object that can be highlighted in a mm/submm-wave survey, if the targeting spectrograph is tuned to a suitable frequency (Frayer et al. 1998; Tacconi et al. 2008); however, this is only possible directly if a redshift is known in advance. Furthermore, these observations are one-by-one in nature, with no multiplex advantage, beyond the production of a serendiptious pencil-beam survey, which sometimes certainly throws up surprises, such as the confirmation of a wide-separation merging pair of galaxies revealed in an observation targeted at the known redshift of one (Tacconi et al. 2006).

From both serendipitous, and thus very incomplete, and targeted, but incomplete, spectroscopy, the range and distribution of redshifts for galaxies selected at submm wavelengths has been established broadly. The bulk of the population of mJy mm/submm-selected galaxies appears to lie at redshifts greater than unity, and certainly extend out to $z \simeq 5$. Individual AGN are known with powerful submm-wave emission all the way to reionization.

There are cases of low-redshift, low-luminosity galaxies with cool spectral energy distributions, that appear in submm-wave images. However, their number is modest (Eales et al. 1999). There are also objects with non-thermal radio spectra, powerful radio-loud active galaxies, perhaps a surprising number, revealed in a relatively wide early survey using the IRAM MAMBO camera, and now from a very much wider multi-band survey from the SPT (Carlstrom, this volume; Vieira et al. 2009). Both of these surveys were conducted at mm wavelengths, where the spectral index of a non-thermal spectrum compared with dust favors the detection of a radio spectrum, but nevertheless, any reasonably deep cm-wave radio image would readily highlight the presence of such galaxies, that lie up to three orders of magnitude away from the radio–far-IR correlation in

[3] wise.ssl.berkeley.edu

the radio loud direction. While these galaxies are present, they appear to be at the few levels of a few per cent.

There are also galaxies that appear to be radio loud owing to an unusually hot spectral energy distribution at far-IR wavelengths. The relative lack of a cooler dust component reduces the submm-wave flux of the galaxies, despite maintaining a large far-IR total luminosity.

A key question that remains is the relationship of the galaxies detected through their submm emission, and the much more numerous samples of near-IR/optical/UV-selected galaxies at comparable redshifts, whether Lyman-break galaxies (Steidel et al. 2004), BzK-selected objects (Daddi et al. 2005), so-called dusty optical galaxies (DOGs; Dey et al. 2008). A detailed comparison requires knowledge of the lifecycles, previous history and subsequent dynamical evolution of the SMGs. It is hoped that this information will be one of the first products from the commissioning of ALMA.

## 3.4 Unequivocal Identification and Results of Follow-Up Observations

The existing status of follow up of galaxies detected here is dominated by the population with spectroscopic redshifts, which are suitable for CO and fine-structure line spectroscopy using radio and mm-wave interferometers. The status of much of this information is listed by Tacconi et al. (2008). The importance of good astrometry is paramount in successful and convincing follow-up. The absolute position of a SMG can only be determined by cross referencing with an image that has higher spatial resolution. This is easy to achieve in a deep optical image, if the optical image can be tied unambiguously to the absolute radio reference frame. Since most SMGs appear in deep radio images, this association can be made. When radio information is not available—which is likely to be the case for some of the most interesting candidates, that could lie at the greatest redshifts—then mm-wave continuum imaging using interferometers is possible (Downes et al. 1999; Younger et al. 1997; Wang et al. 2008; Cowie et al. 2009). However, these instruments have small fields of view, and the astrometry of the image is determined by the position of the bright phase-reference calibrator that is employed. The position of the SMG in the interferometric image is thus known very precisely compared with the absolute reference frame; however, the position of overlaid images taken at other wavelengths is less certain, and fractional arcsec offsets can lead to different conclusions about the effect of a foreground gravitational lens, or about the internal distribution of luminosity in the far-IR and optical bands.

ALMA will address many of these issues by detecting the emission from a larger fraction of galaxies in the field, and providing morphological information. Nevertheless, it remains important to test and verify identifications of the most enigmatic sources with some scepticism. It remains interesting to note that some of the most luminous, apparently distant galaxies detected at submm wavelengths are extremely faint in other bands.

## 3.5 Identifying Redshifts

Systematic spectroscopy at optical/near-IR wavelengths can give a good multiplex advantage, if the source density exceeds about 1 arcmin$^{-2}$. while this was achieved by the early deep submm-wave surveys, recent surveys have typically moved to generate sources densities that only land a small handful of potential targets on the mask area of an efficient multiobject spectrograph. This disadvantage can be overcome by searching in fields with a wealth of other data, where a substantial program of multi-purpose spectroscopy is being carried out for a wide range of different science applications. The clearest examples of such fields include the ultradeep GOODS, and wider AEGIS (Davis et al. 2007) and COSMOS (Scoville et al. 2007) areas. The detection of far-IR confirmed galaxies in COSMOS has been described by Capak et al. (2008), while painstaking searches in GOODS have revealed otherwise unrecognized counterparts to optically-dark SMGs (Wang et al. 2008; Cowie et al. 2009), ultimately relying on the high-spatial resolution of continuum detections using mm-wave interferometers to highlight the interesting objects. This work confirms that the redshift distribution of far-IR-identified galaxies is very broad, and that relatively bright SMGs can still be plausibly at high redshifts. Circumstantial evidence for this also comes from the analysis of the *Spitzer* continuum properties of detections using the 2.5 m-aperture BLAST balloon-borne telescope (see Pascale et al. 2009). The merging of data from SPT and *WISE* promises to confirm the true number of bright high-redshift candidates. While these objects are far too rare to have any consequence for reionization, the details of how to assemble a very massive, very luminous galaxy in the first Gyr after the Big Bang will inevitably lead to new insights into the process of galaxy formation, especially perhaps in the highest density regions where high peaks are expected to appear first in the sea of growing density perturbations.

### 3.6 The Outcome of Follow-Up Observations

**Stellar Masses** Sensitive *Spitzer* mid-IR images allow the redshifted stellar spectral energy distribution to be derived for potential counterparts. Combined with optical imaging, this allows a reasonable fit to stellar evolution libraries in order to estimate the age, mass, and extinction of escaping starlight (Hainline et al. 2009; see also Borys et al. 2005 and Smail 2002). The precision of these results depends on the accuracy of the model, and the *unknown* degree of inhomogeneity in the source. The indication is that SMGs have built up a substantial stellar mass when detected, that their stellar populations are consistent with ages of only a few Myr, and that if anything, their associated X-ray properties indicate that the formation of stars might have preceded the mass of a supermassive blackhole (SMBH) that would be required for the galaxies to lie on the present day SMBH-stellar bulge mass relation (Borys et al. 2005). A substantial uncertainty is differential extinction from place to place in the galaxy, and the presence of short lived, very luminous AGB stars with powerful near-IR emission (Maraston et al. 2006), which are not typically included in stellar synthesis models, and which can reduce the effective age and mass of an inferred starburst by a factor of several.

**Dynamical Masses from near-infrared and CO Spectral Line Emission** Masses of molecular gas can be derived based on the intensity of CO mm-wave line emission, along with dynamical measurements from their width and those of nebular lines. The results are consistent with a significant reservoir of gas remaining in these sources, and a gas-depletion timescale of order 100 Myr. The inferred total dynamical masses inferred from the profiles of these lines, either assuming a virialized cloud of gas, or a disk (Tacconi et al. 2008) are consistent with the line intensity.

**X-ray Observations and other AGN Signatures** Ultradeep X-ray observations are essential in order to detect the expected faint emission from star-forming galaxies at high redshifts. Even a substantially brighter hard X-ray spectrum expected from the environment of an AGN requires some significant depth. Alexander et al. (2005, 2008) have described the properties of the X-ray spectra, in the GOODS-N region, where *Chandra* data is deep enough to provide enough detections to help provide spectral information, and subject to the caveat that a Compton-thick overburden of hydrogen could make a more luminous intrinsic X-ray source invisible, is that of order 10% of the total power emitted by SMGs is produced by accretion onto a blackhole.

Optical and near-IR spectroscopy from the ground (Chapman et al. 2005; Swinbank et al. 2004) provides evidence from the presence of AGN from optical/UV line strengths and ratios, and from broad H$\alpha$ emission. The presence of an underlying AGN component at the 10–20% level is consistent with the detected broad component after stacking the full sample of spectra.

Mid-IR spectroscopy from *Spitzer* (Borys et al. 2006; Ménendez-Delmestre et al. 2009) shows a consistent picture, in which a starburst contribution with spectral features from polycyclic aromatic hydrocarbon molecules that are typical of local starbursts, combined with an additional, less-energetic red feature-free AGN template contribution can described most individual sources. About 10% of sources do show mid-IR spectra consistent with a dominant AGN.

**Sizes** Current size estimates are only available as limits imposed by the size of the synthesized beam in mm-wave interferometer maps (e.g., Younger et al. 2007; Tacconi et al. 2008). Sizes consistent with a few kpc are typically derived. In some cases, there is significant evidence for multiple components of emission, separated by many beams, of order 20–30 kpc (Tacconi et al. 2006).

ALMA and extended Very Large Array (eVLA) observations will enable direct measurements of sizes, and provide resolved images at radio and (sub)mm wavelengths. Extended non-thermal radio continuum emission is a proxy for the extent of the far-IR emission (Chapman et al. 2004, 2008; Casey et al. 2009), currently available in only a few fields tend to indicate that a substantial number of SMGs have emission extending over many kpc.

## 4 Larger-area, Deeper Surveys

The move to covering fields of view in excess of $\simeq 1\,\mathrm{deg}^2$ has been led by the desire to make blind surveys for the Sunyaev-Zeldovich effect (SZ) signal from previously unknown clusters of galaxies. Long sought for individual known targets, the relatively simple physics of the ionized intracluster medium provides a way to assess the mass and dynamical state of the most massive bound structures in the Universe. The development of wide-field imaging instruments, first BOLOCAM at the CSO, based rather directly on technologies developed for the *Herschel*-SPIRE camera—as does BLAST—and exploiting tools developed by a variety of cosmic microwave background (CMB) experiments, has enabled limits to be placed on the abundance of SZ clusters, which has consequences for the form of evolution of the geometry of the Universe, and for the normalization of the amplitude of overdensities (via $\sigma_8$). Several dedicated survey telescopes/instruments have been commissioned for this goal, including SPT (see the contribution by Carlstrom), a dedicated camera on the APEX, ASTE, and ACT telescopes. At recent meetings Joaquin Vieira has presented stunning images of the $100\,\mathrm{deg}^2$-scale images of the CMB taken at three mm-wave frequencies using SPT, that clearly show images dominated by the 1 deg scale primary CMB fluctuations, with the detection of positive beam-shaped point sources that are a mix of both low-redshift galaxies in the field and the brighter cousins of SMGs, and negative point sources (absent at 214 GHz) that are SZ clusters. This makes a big step forward over the limits on bright sources imposed by mining galactic survey fields (e.g., Barnard et al. 2004). The ability to detect many tens of dusty galaxies, with a smattering of radio-loud non-thermal contaminants, albeit contaminants that can be readily recognized from their color in the SPT images, has provided a valuable additional constraint to the abundance and properties of the most extreme objects in the Universe, and provides insight into their properties, based on their multiwavelength properties. The only downside to this, is that with surface densities of order $1\,\mathrm{deg}^{-2}$ there is no possibility of enjoying a multiplex advantage in following up these galaxies. Each becomes a "named object" that requires dedicated spectroscopy. In the far Southern sky, this is relatively difficult, owing to the available resources.

The importance of conducting surveys that cover large $100\,\mathrm{deg}^2$ areas cannot be overstated. Even in the largest fields with excellent deep multiwavelength data available from a suite of the best telescopes, such as COSMOS (Scoville et al. 2007) and AEGIS (Davis et al. 2007), the 30–50 Mpc extent of the imaged region is smaller than the 100 Mpc comoving scale of the largest structures seen in the distribution of galaxies today. In order to map several of the bubbles in the large-scale structure of galaxies at each redshift sampled by a survey, it is necessary to extend the angular coverage of the images by a linear factor of at least 3, pushing out to surveys that extend 5 deg across. This remains a tough challenge for any space-based deep survey. However, it is something that CCAT is in an ideal position to carry out.

The forthcoming SCUBA-2 camera at the JCMT, a 2nd–3rd generation submm-wave instrument should allow mapping over comparable areas of sky, but with 15 arcsec resolution. However, regardless of when the first results come from SCUBA-2, SPT images have provided a prelude to large-field observations at mm-wavelengths, detecting some of the most extreme objects. Large-area surveys should also soon be made using the *Herschel*-PACS and SPIRE instruments, building on depth and size of the recent images reported by the 2.5 m aperture BLAST balloon experiment (Pascale et al. 2009), which provides a slightly-more-modest resolution image of a field large enough to be respectable from *Herschel*. While the stability, pointing accuracy and near permanent availability deriving from an L2 orbit will render the scientific legacy of *Herschel* very valuable, something that Tom Phillips has helped ensure based on careful stewardship of the observatory through difficult times of politics and funding, a taster of the likely results from the SPIRE surveys is already available.

The next-generation multi-band surveys over representative volumes of the Universe will be made and followed up using CCAT and the instrument suite that is being assembled for it. This observatory will be a worthy successor to CSO, and allow the most rigorous and complete follow-up of targets selected from *Spitzer*, SPT, *Herschel*, *Planck*, *WISE*, SCUBA-2, and MKIDCam surveys along with a deep survey capability to save time for, and feed ALMA.

### 4.1 Understanding Processes Nearer to Home

While the developments have been important for understanding galaxy formation, they have of course been even more crucial for understanding star formation, where optical depths at visible and near-IR wavelengths preclude an understanding of anything but the outermost layers of molecular clouds. Note that there is every indication that the small-scale processes seen in the Milky Way are also taking place in distant galaxies, and so there is a direct link, although the luminous objects detected by the restframe far-IR emission at cosmological distances dwarf the Milky Way's level of activity, and appear to consist almost entirely of baryons in the state present in the most active star forming regions of our galaxy.

In order to understand the range of processes that act to produce dramatic bursts of star formation and AGN fueling activity in distant galaxies, it remains essential to study the processes of star formation and feedback in our in active star-forming regions of the Milky Way, and in nearby galaxies. At present all explanations of the appearance and nature of distant SMGs treat them as scaled up versions of nearby galaxies, and some of the most intensive attempts to treat the radiative transfer of energy from star formation and AGN constrain the basic geometry to be a disk, in marked contrast with the appearance of any local ultraluminous galaxy: even in the case of M82, which does have a disk-like geometry, the effects of winds and bubbles have substantially wrecked any coherent structure of the interstellar medium.

The only forthcoming instrument that will delve into the conditions down to stellar radii in the Milky Way, and into the densest cores in molecular clouds in nearby galaxies is ALMA. Other facilities will allow ALMA to spend its time imaging the most interesting regions, and not searching for them. Nevertheless, it is interesting to note that the most expensive ground-based astronomical instrument ever brought into service relies for its performance on the SIS junction that Tom Phillips introduced to astrophysics.

## 5 Final Thought

In his summary of the meeting, Tom Phillips stated that a cryogenic space-borne interferometer with a collecting area of about three times that of ALMA would be necessary to understand the processes of star formation. This is a bold plan indeed; however, ground-based interferometers and single-aperture telescopes have revealed much about galaxies in the last two decades. With the forthcoming results expected from *Herschel*, *Planck*, ALMA, and CCAT, in ten years' time we can look back on this meeting and check the prescience of this intuitive statement.

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